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**INTEGRAL GLASS ENCAPSULATION
FOR SOLAR ARRAYS**

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**A. R. KIRKPATRICK
P. R. YOUNGER
W. S. KREISMAN**

QUARTERLY PROGRESS REPORT NO. 3

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Prepared for:

Jet Propulsion Laboratory
CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California 91103

Prepared by:

SIMULATION PHYSICS, INC.
Patriots Park
Bedford, Massachusetts 01730

ABSTRACT

This is the third quarterly report under a fourteen month program to develop integral glass encapsulation for solar cell arrays. The report describes the status of development to establish techniques for employing electrostatic bonding in conjunction with terrestrial solar cells.

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1.0 INTRODUCTION

This is the third quarterly report under a program to develop integral glass encapsulation for solar cell arrays. Progress to date demonstrates that integral glass encapsulation by electrostatic bonding is unquestionably feasible. Integral glass has promise for major improvements in module performance and stability at substantially lower cost than can be anticipated using organic material encapsulants.

Electrostatic bonding can be used to form a permanent adhesiveless seal between silicon solar cells and a sheet of glass. This program involves investigation of the requirements and limitations of this process for array encapsulation, development of utilization techniques and evaluation of integral module test configurations. At this time it is evident that the ESB process is fully compatible with the components of the solar cell array and techniques for its use have been established. All evaluation data now available suggest that the electrostatic bond is extremely strong and apparently absolutely stable. A correctly designed and assembled integral glass solar array should be characterized by excellent functional lifetime.

Program status at the time of the second quarterly report was that, using an interim electrostatic bonder facility, the basic mechanical techniques necessary for solar

array assembly had been developed. In particular, necessary characteristics of the glass had been identified, large area bonds were being routinely made and ability to deform the glass around thick contact grid structures on terrestrial solar cells during the bonding process had been demonstrated. No multiple solar cell or electrically functional test samples had been produced as these tasks required the availability of a controlled environment bonder facility which would perform the bonding process under vacuum or inert gas.

During the past quarter the controlled environment bonder has become operational. Developmental work has progressed rapidly. Multiple cell and electrically functional samples have been produced. First successful integral module configurations have now been demonstrated.

2.0 PROGRAM STATUS

During this reporting period the controlled environment bonder became fully operational. Throughout the first month of this quarter the interim bonder was still in constant use, but the improved quality of samples bonded under controlled environments is so marked that continued operation of the atmospheric bonder became pointless.

Efforts of the past three months involved the following:

- (1) Assembly and testing of the controlled environment bonder.
- (2) A partial assessment of the effects of various atmospheres, including nitrogen, forming gas, argon, and vacuum, on bond quality.
- (3) Contact and interconnect metallization studies including evaluation of bonds formed with evaporated films of several refractory metals. Bonding with silver. Bonding with silk screened metallization on glass.
- (4) Glass surface evaluation including bonding to as-pressed 7070 glass, repressing of irregular glass surfaces, and formation of cavities in glass by pressing.
- (5) Preparation of samples for testing shear strength and hermeticity of electrostatic bonds.
- (6) Module design specification and development.

2.1. Controlled Environment Bonder

The controlled environment bonder became operational at the end of December 1976. A photograph of the apparatus appears in Figure 1. With this equipment it has been possible to bond a wide range of materials which would not bond in an oxidizing atmosphere. This bonder, capable of handling eight inch square samples, has already demonstrated the feasibility of large area bonds by simultaneously bonding five 2 1/4 inch diameter solar cells to single pieces of glass. An example is shown in Figure 2. A Mechanical vacuum pump brings the chamber pressure, for vacuum bonding, to the working level of 10 μ m Hg. within 5 minutes. A gas manifold allows the introduction of four separate gases when backfilling is desired. A diffusion pump may be added for lower pressure during vacuum bonding, but at present this appears unnecessary. Bonding temperature and voltage limitations are in excess of 620°C and 1500 volts respectively.

With this bonder, it is now possible for the first time to evaluate the effect of atmospheric composition on the quality of electrostatic bonds. Furthermore it is now possible to join materials that are not bondable in air. Bonding has been performed with a number of materials in atmospheres of nitrogen, forming gas, and argon as well as under vacuum. Use of argon has been limited due to the rather low voltage breakdown strength of this gas. Bonds formed

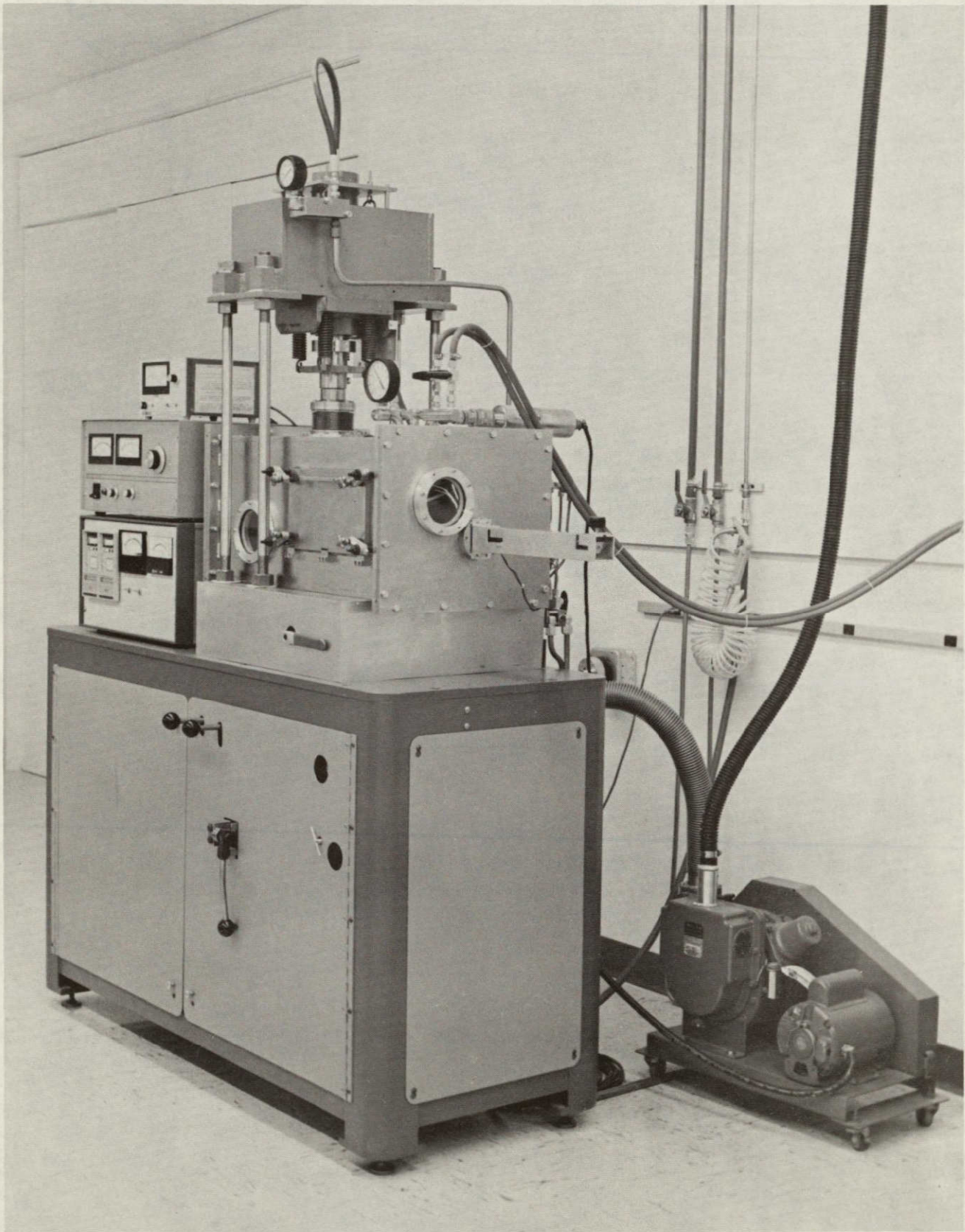


Figure 1. The Controlled Environment Bonder

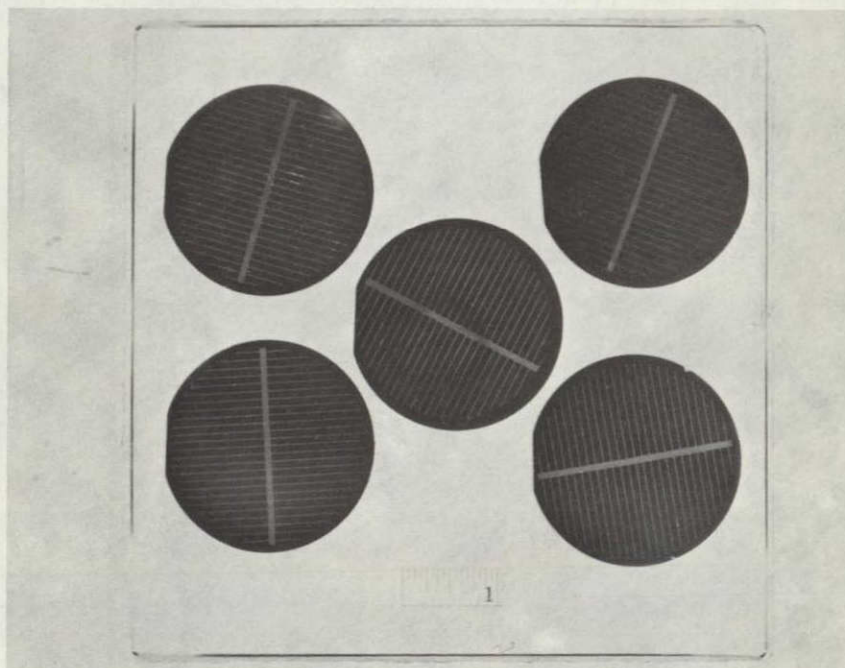


Figure 2. Five 2 1/4 Inch Diameter Solar Cells Electrostatically Bonded to a Single Sheet of 7070 Glass

in atmospheres of nitrogen and forming gas are much cleaner than those formed in air but vacuum bonds are superior, at least in appearance. A full evaluation of the effects of atmospheric composition would require, at a minimum, measurements of bond strength as a function of bonding environment. In the case of metals used as solar cell contacts, a measurement of contact resistance to silicon will also be necessary. A number of samples, designed to test bond shear strength and hermeticity have been prepared. Preparation of such test samples will continue.

For the present, solar cell bonds are being made primarily under vacuum. An additional advantage of vacuum bonding is that the possibility of trapping gas bubbles between bonded surfaces is greatly reduced.

2.2 Metallization Studies

Metals that are candidates as electrical interconnects and feedthroughs in electrostatically bonded solar cell modules must meet several requirements. These include compatibility with silicon (no low temperature eutectics and low diffusion rates into silicon), low contact resistance to silicon, low bulk resistivity, ability to form electrostatic bonds, and good adhesion to glass. Some of these constraints may be relaxed if more than one metal is used. However,

module processing would be simplified if a single material satisfying all these requirements were found.

At the beginning of this program, candidate materials for use as solar cell metallization were limited to silicon, aluminum and silver. Silicon was considered because it was known to form good electrostatic bonds and aluminum and silver were desirable because they are low resistivity metals and are routinely used for solar cell contacts. All three materials have drawbacks. Silicon, even when heavily doped, has at best moderate conductivity. Aluminum, although it was shown early in the program to bond readily to glass, has a 577°C eutectic with silicon. This eutectic would put an upper temperature limit for bonding which might make significant glass deformation impossible. Attempts to bond silver to glass in the interim bonders were unsuccessful.

Since all three materials had limitations, other candidates were investigated for one step metallization. Most of these potentially usable materials were refractory metals. Chosen for investigation were molybdenum, tantalum, titanium, and chromium. Evaporated films of these metals on 7740 glass were prepared and bonded to matching pieces of 7740. All four metals bonded readily in both vacuum and nitrogen atmospheres. Some bonds were done in forming gas. These too were successful. No qualitative differences in bond strength could be found immediately since all bonds were mechanically

sound and unaffected by thermal cycling between liquid nitrogen and room temperatures. Visually the vacuum bonds were cleaner than those done in nitrogen or forming gas. Samples bonded in nitrogen showed some discoloration that was generally absent from vacuum bonded pieces. The addition of 5% hydrogen (forming gas) did not result in a noticable improvement over bonds formed in pure nitrogen.

Electrical properties of these metals have important bearing upon their use in solar cell modules. Quantities of interest are the resistivities of thin evaporated films and their contact resistance to bare silicon. Measurements taken on thin films of all four metals indicate resistances at least an order of magnitude higher than in the bulk state. These high values make meaningful measurement of contact resistance to silicon difficult.

At this time it can be concluded that all these metals can probably be used for metallization in solar cell modules, but some development work would be required before films with the proper electrical characteristics could be made. For the present program only metals of previously proven applicability will be used.

As mentioned above, attempts to bond silver to glass in the interim bonder had failed. However, under vacuum and pure nitrogen evaporated films of silver did bond to 7740 glass.

These preliminary bonds covered only 70 to 80% of the interface area, indicating that while bonding silver is indeed possible it may prove difficult to produce 100% bonds routinely.

Silk screening is an inexpensive alternative to applying metallization via vacuum evaporation. Original attempts made with the interim bonder to bond metallized solar cells to 7740 glass, coated by JPL with silk screened metallization, were not successful. Arcing through the metallization combined with oxidation to completely destroy cell performance. A second set of samples with silk screened silver on 7070 glass was provided by JPL. A cell wafer without any front contacts was bonded to the metallized glass. Continuity along the contact bar was not broken at the cell edge. The bonded cell retained its full open circuit voltage but output current was reduced by series resistance of approximately one ohm. The bonded unit I-V characteristic is given in Figure 3. This preliminary result indicates considerable promise for silk screen application of metallization. Further investigation of ink composition, firing temperature, and deposition thickness will be necessary to optimize the process. Bonding tests will be made using samples of other materials that have been supplied by JPL:

2.3 Glass Surface Evaluation.

Code 7070 glass has been chosen for use as a solar cell encapsulant. This material has been selected because of its

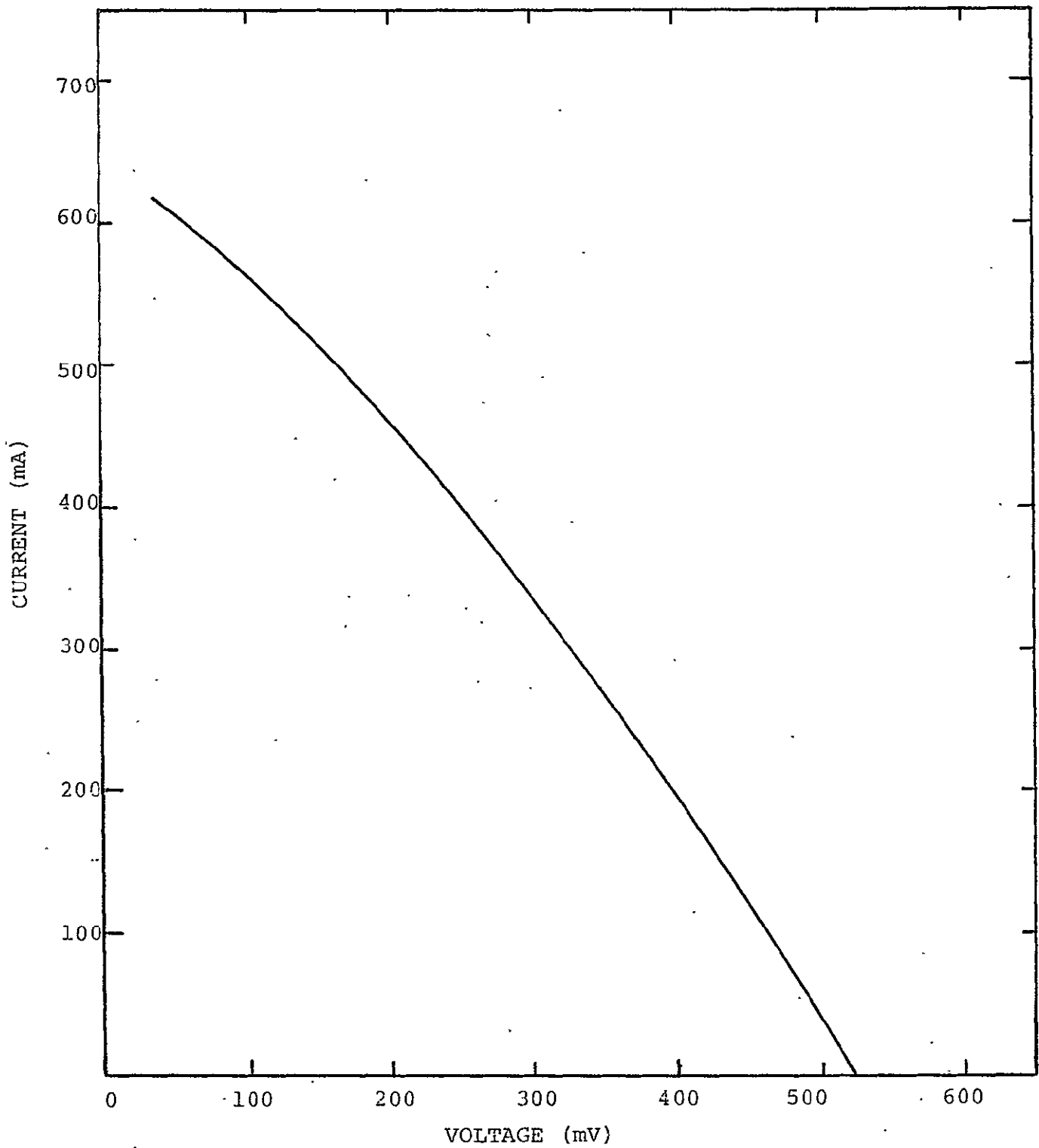


Figure 3. I-V Curve of Unmetallized Cell Bonded To 7070 Glass With Silk Screened Metallization

excellent thermal expansion match to silicon. Its viscosity is low enough ($\approx 10^{11}$ poises at 550°C) to permit considerable deformation during bonding.

Currently 7070 glass is produced only by pressing in a mold. This process yields two distinctly different surfaces. The better side is relatively smooth with occasional rough spots caused by the bottom of the mold. The poorer surface is very irregular with thickness discontinuities as large as .01 inch. These irregularities are sufficient to prevent optical transmission of clear images.

At first it would appear that this glass could not be used for bonding in the as-pressed condition. Initially only 8mm thick 7070 was available. This thickness was not convenient for solar cell encapsulation by electrostatic bonding so that 8mm glass was ground to 1/8 inch and polished since the ground finish was translucent. Recently 4mm thick glass has become available. Since this thickness is reasonable for encapsulating, experiments have been done to determine if electrostatic bonds can be made over the entire surface of an as-pressed piece of this glass.

At 550°C, 100% bonds were easily made between silicon wafers and the better glass surface. Lowering the temperature caused small unbonded regions to appear. It was also possible to bond to the poorer surface at 550°C. However, great care was necessary to prevent breaking of the silicon when it first contacted the high spots on the rough surfaces.

Preliminary attempts were made with the interim bonder to repress the 7070 glass surface. Initially graphite was used as a pressing surface since it would not stick to the glass. At temperatures between 550°C and 600°C optically clear surfaces could be produced on as-pressed 7070. The smoothness of these surfaces were limited only by the quality of the graphite surface.

Using stainless steel dies even smoother surfaces could be obtained. However, only polishing the stainless steel surface would prevent adhesion of the steel to the glass and even a 1 μ m surface would stick due to the oxide formed during a single use. It was still possible to cause substantial deformation of the glass. A 2 1/2 inch diameter cavity of 0.010 inch depth was pressed into a piece of 7070 using highly polished stainless steel.

Further pressing experiments will be made in the controlled environment bonder where rapid oxidation of steel surfaces is not a problem. Use of mold release compounds as discussed below and in an earlier report⁽³⁾ will also be considered.

2.4 Sample Preparation

Samples have been provided to JPL for evaluation of shear strength and hermeticity of electrostatic bonds formed between pieces of glass with evaporated interfacial coatings.

Initial simple pull tests and thermal cycling tests indicated that electrostatic bonds are strong and durable but did not provide quantitative measure of bond integrity.

Shear test samples supplied to JPL consisted of two 1 inch x 3 inches pieces of 7740 glass bonded together over an overlap region 1 1/2 inches long. Bonding was accomplished through an interfacial layer of silicon or silicon monoxide evaporated onto one piece of glass. One half of the samples were singly bonded, that is a bond was formed between the interfacial coating and the overlaid piece of bare glass. Since it was not known whether the electrostatic bonds or the evaporated coatings would fail first, a second set of samples was prepared in the same way as the first and then bonded a second time, in the reverse direction. The purpose of this second process was to bond the evaporated coating to the substrate glass to which it was originally applied. With these pairs of samples it is possible to measure the strengths of electrostatic bonds and compare them to the adhesion of evaporated coatings.

Tests performed at JPL showed no bond failures under shear forces reaching 500 psi. It was not possible to apply more force to the samples without breaking the glass at the connection to the test equipment. Accordingly a new test configuration, shown in Figure 4, has been defined. Samples of this style are currently being produced.

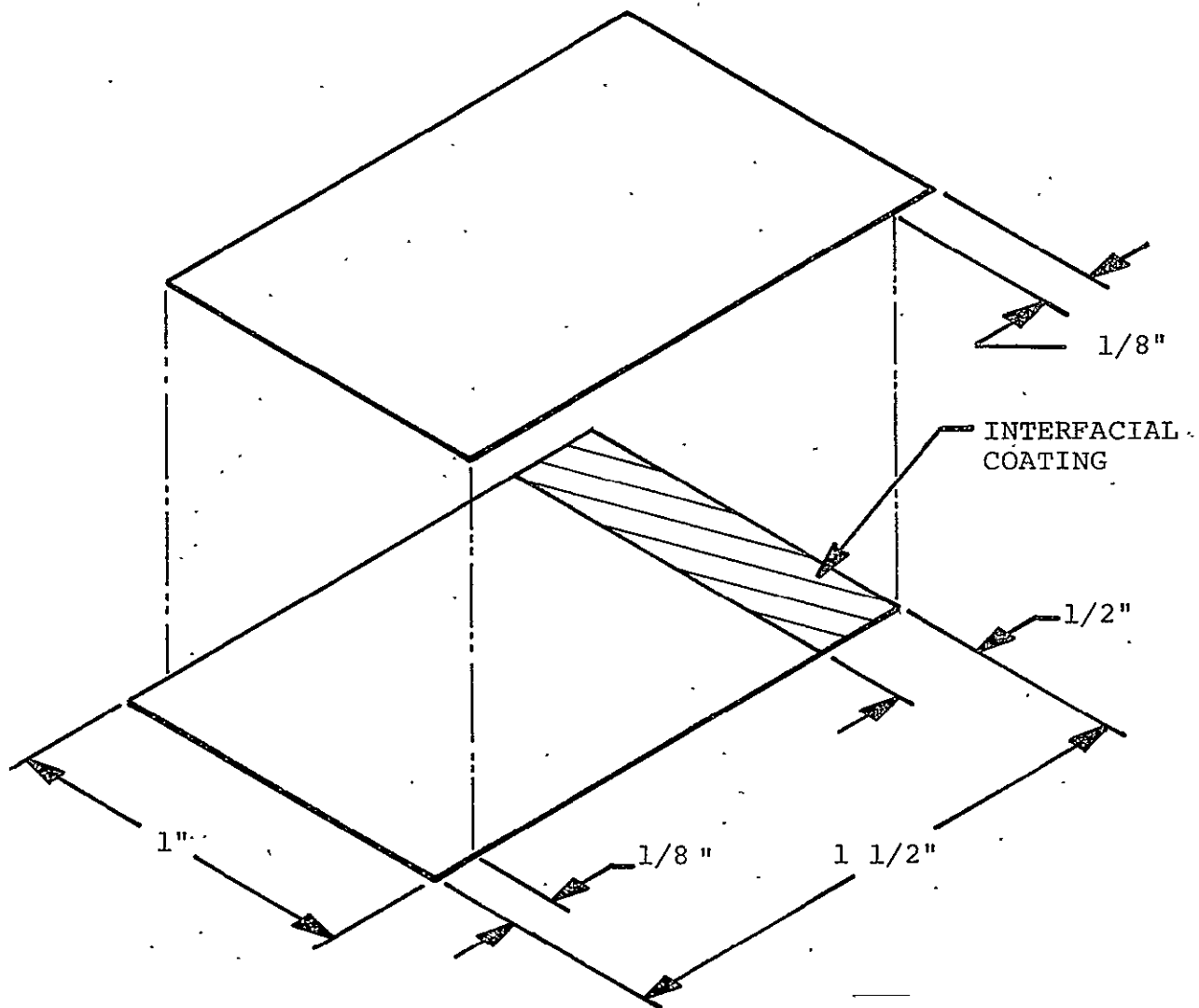


Figure 4. New Shear Strength Test Configuration .

In addition to testing under shear loading, these samples were immersed in boiling water for a period of two weeks. Again, no bond failures, even local, were observed.

Samples have been prepared to test the hermeticity of electrostatic bonds formed with aluminum and silicon. A 2.5" x 2.5" x .060" cavity was made in pieces of 7740 glass by sandblasting. A second square of glass with an evaporated coating was placed over the cavity and bonded around the 1/4 inch wide perimeter. Variation in cavity depth resulted in some very weak samples, including one vacuum bonded piece that imploded upon exposure to atmospheric pressure. Additional samples will be produced using 7070 glass with a milled cavity, the depth of which has been held to a tolerance of a few thousandths of an inch. Evaluation of the first set of samples is in progress.

All tests made to date indicate that glass encapsulated solar cell modules made by electrostatic bonding will have excellent reliability. The long term performance of such modules should be superior to all other existing systems.

2.5 Module Design and Production

Under this program three module types will be identified and produced. Design details for each type will be determined as the program continues, but the basic

configurations have been determined. Type I will incorporate electrostatic bonding in the simplest form. Four 2 1/4 inch diameter cells will be bonded to a piece of metallized 7070 glass which will form the module front. Silver ribbon will be soldered to the cells and metallized glass as needed to form interconnects. Output leads will be in the form of binding posts attached through holes drilled in the glass. The cell and glass back surfaces will be coated with a waterproofing compound to complete the module. This design will demonstrate the applicability of electrostatic bonding to solar cell encapsulation and yet will be relatively inexpensive and easy to produce.

Other module types will involve more electrostatic bonding. In particular, Type II will be similar to Type I but with a glass back electrostatically bonded to the front. This glass will have a recess to accommodate the solar cells. Formation of the recess will be either by pressing or milling. Interconnections will be as in Type I but welded rather than soldered. Output connections, the design of which has not yet been finalized, will probably be via evaporated films.

Type III will be the most sophisticated as regards electrostatic bonding. It will be totally integral with no preforming of the glass. This type will be the most difficult to produce since the front and back pieces of glass will have to be completely deformed around the solar cells during the bonding.

Considerable development of these three types has been achieved. A partial prototype five cell module of the first kind has been delivered to JPL. It consisted of one piece of glass metallized everywhere except for five circular openings for the cells. The contact grid pattern on the cells, just overlapped the glass metallization at the edge of these circles. The five cells were thus connected in parallel.

The I-V curve of this module, Figure 5, shows degradation of cell performance. In particular there is considerable shunting of the junctions. Shunting is apparently caused by the metallization wrapping around the cell edge where the cell deforms the coated glass. Because the junction is extremely shallow, almost any deformation can cause shunting. Figures 6 and 7 show individual unshunted and shunted cells of the module of Figure 5.

A solution to the shunting problem has been found in the metallization pattern of Figure 8. A ring of metal, slightly smaller than the cell, is applied to the glass. This ring serves to collect the current from the contact grid of the cell. Current is then fed to the main metallization which surrounds the cell by narrow radial fingers. Since only a few percent of the cell edge area is crossed by the fingers, shunting is much reduced.

Figure 9, shows I-V curves, taken at four different intensities, of a 2 1/4 inch diameter cell bonded to this new

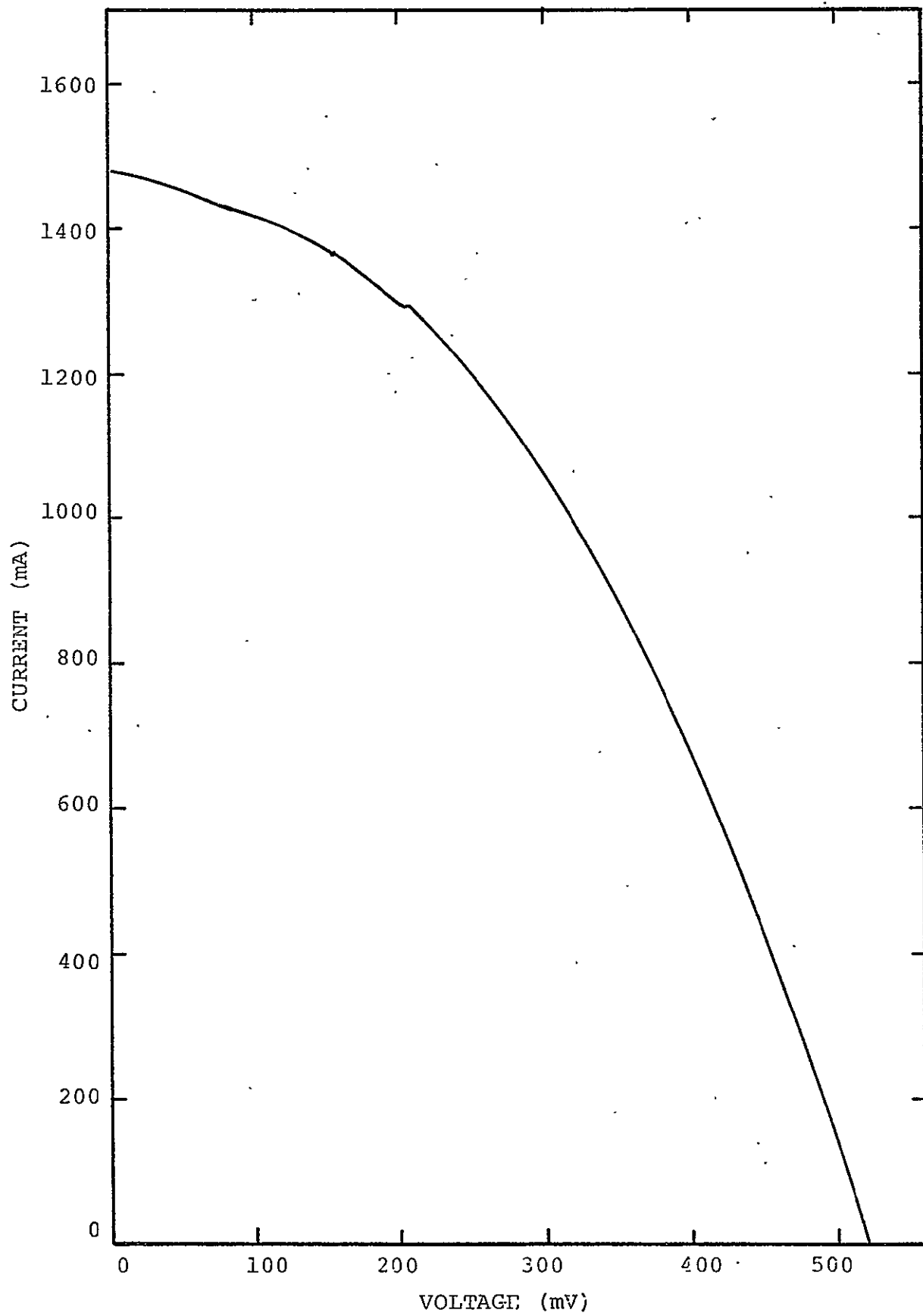


Figure 5. I-V Curve Five Cell Module

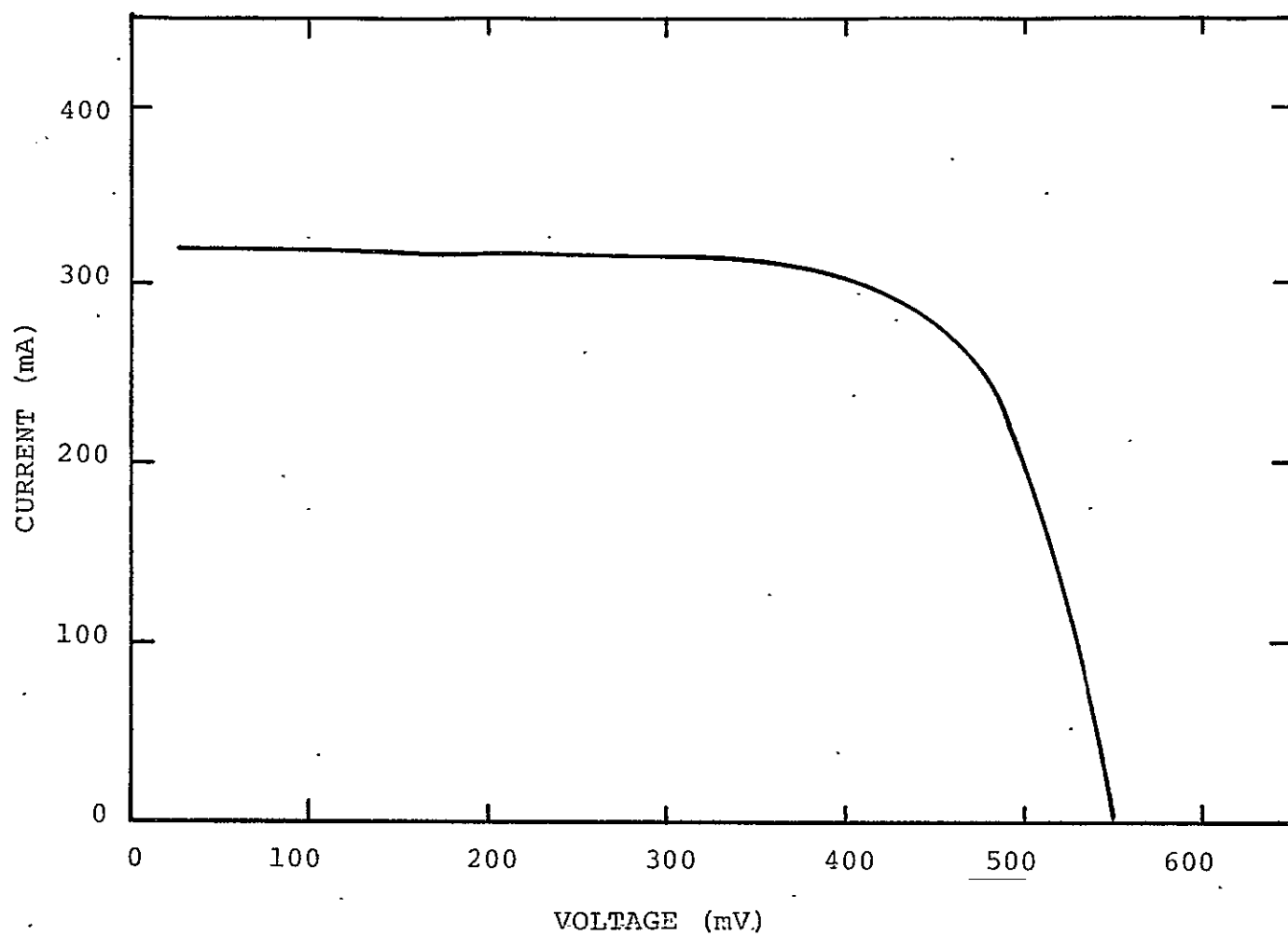


Figure 6. Individual I-V Curve of Unshunted Cell From Five Cell Module

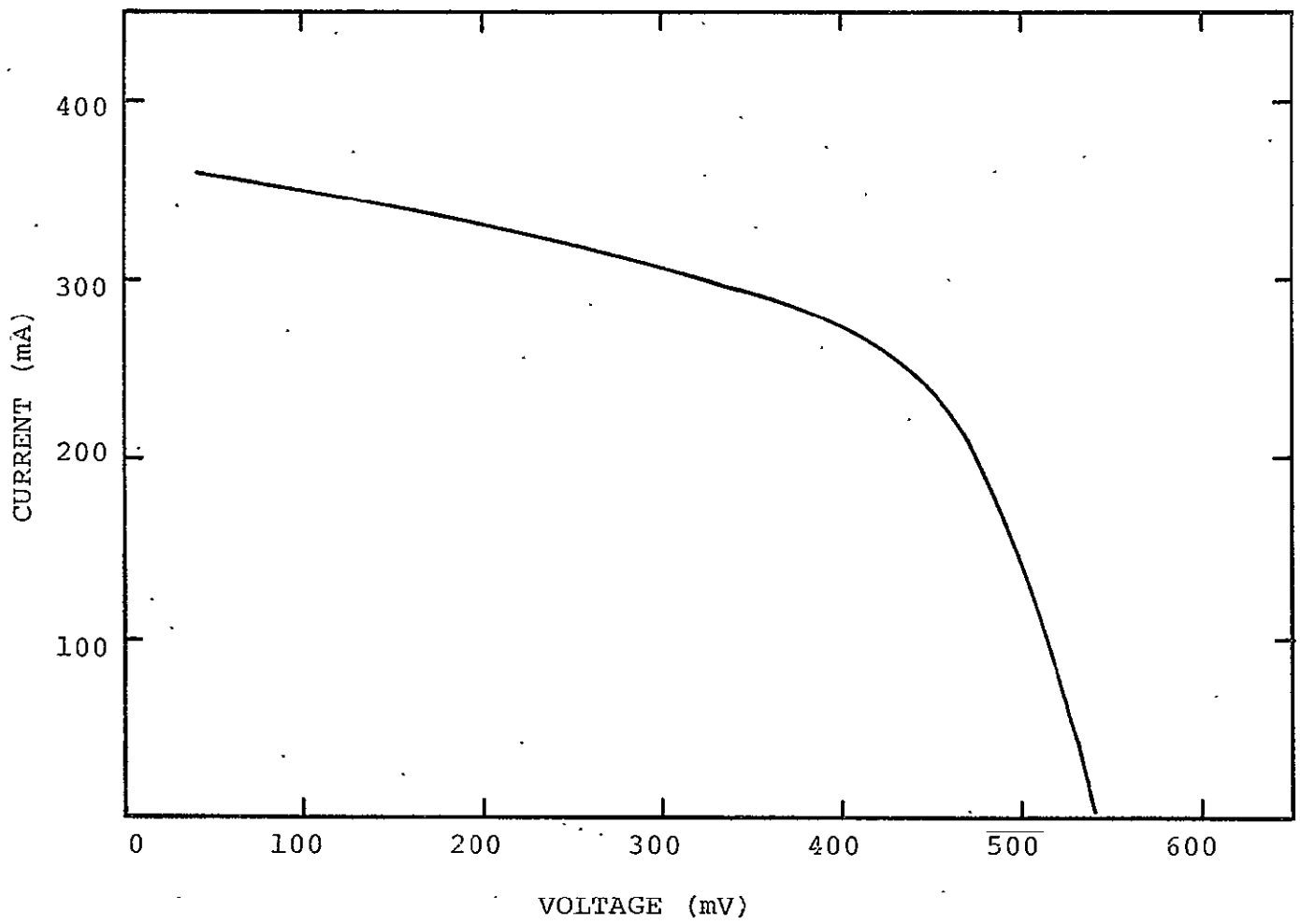


Figure 7. Individual I-V Curve of Shunted Cell From Five Cell Module

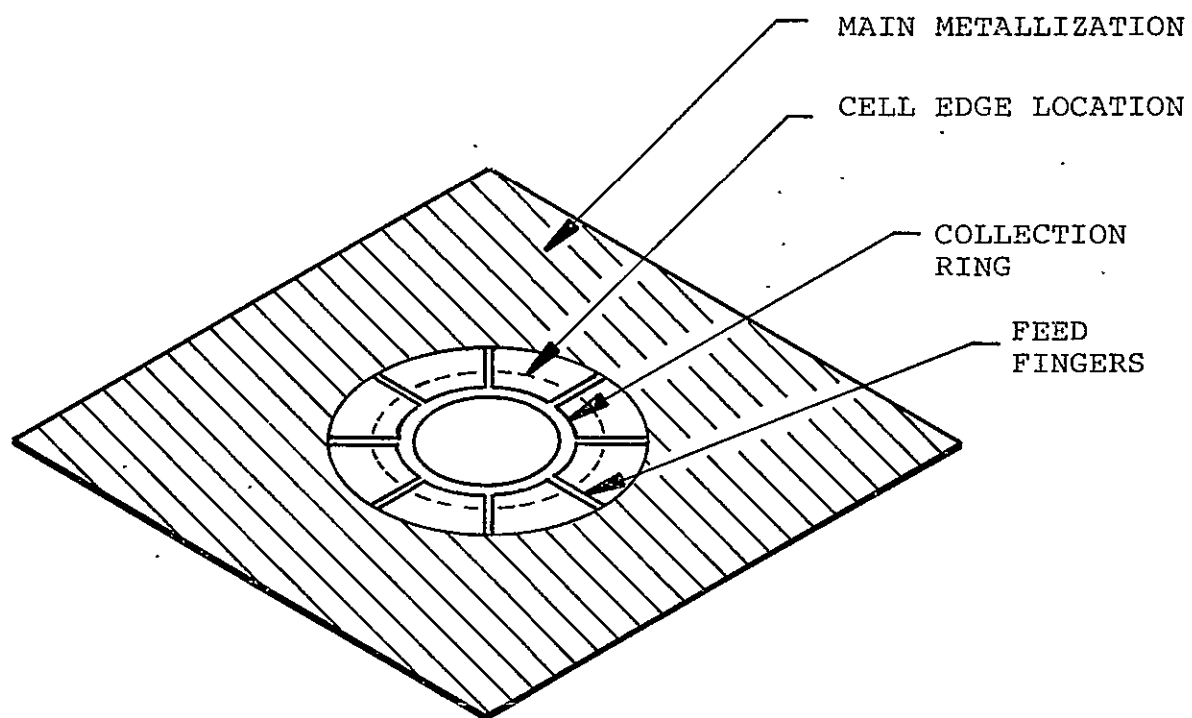


Figure 3. New Metallization Pattern

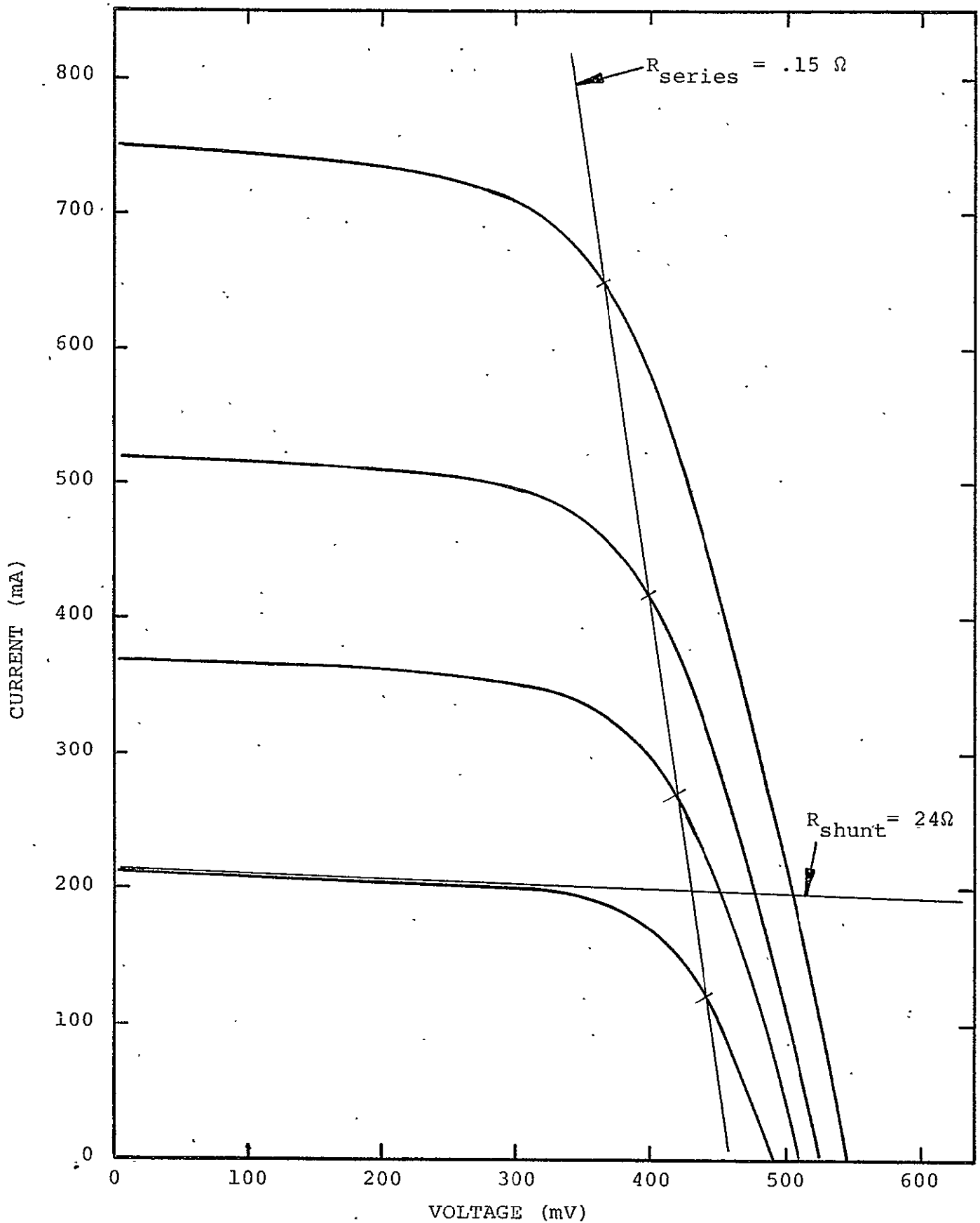


Figure 9. I-V Curves Taken at Four Different Incident Intensities for a Single Cell Bonded to the Pattern Shown in Figure 8. Lines Drawn are for Calculating Shunt and Series Resistances

metallization pattern. Shunting is observed to be modest at approximately 24 ohms. Additional improvements are expected. The total series resistance of and to the cell is 0.15 ohm.

A four cell module, connected in series has been produced using this new metallization pattern. A photograph is shown in Figure 10. The Air Mass Zero I-V curve of this assembly is shown in Figure 11.

Several materials have been investigated for use as a backing for Type I modules. Two commercial asphalt base products were tried. Pieces of glass were coated with each material and after curing, these samples were boiled in water for five minutes.. Both coatings were then easily peeled off of the glass.

A silicon rubber, General Electric RTV-11, was applied to glass which had been prepared with SS-4004 silicon primer. Good adhesion was attained and boiling in water for two hours had not affected the quality of the seal. Other candidates will be investigated..

For Type II modules a recessed back will be needed. These backs can be milled to the desired configuration, but it may be feasible to press this recess into the glass. Tests described above indicate that this will be possible.

Production of Type III modules presents the most serious problems. The conditions required to produce the needed deformation have, in the past, resulted in adhesion

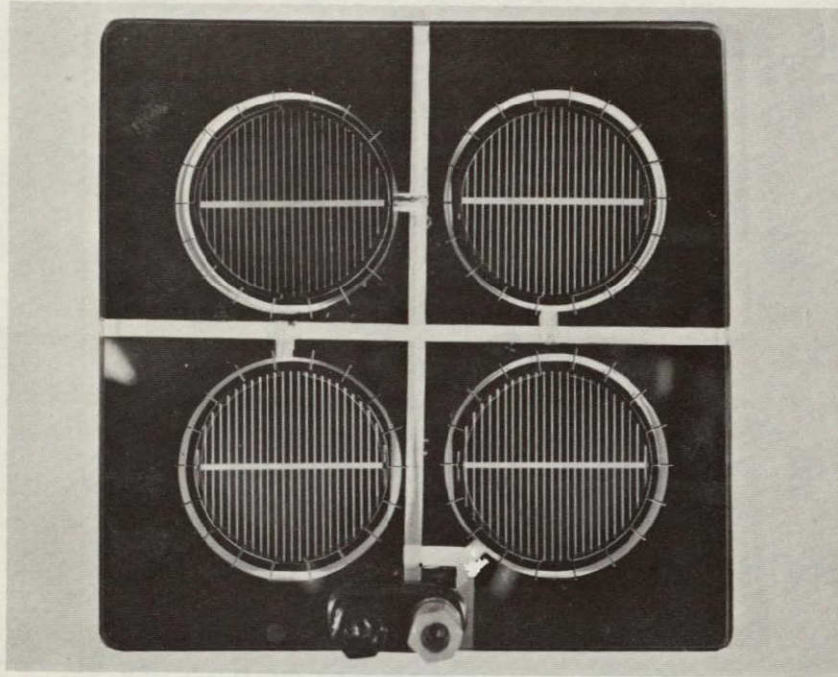


Figure 10. Four Cell Series Module

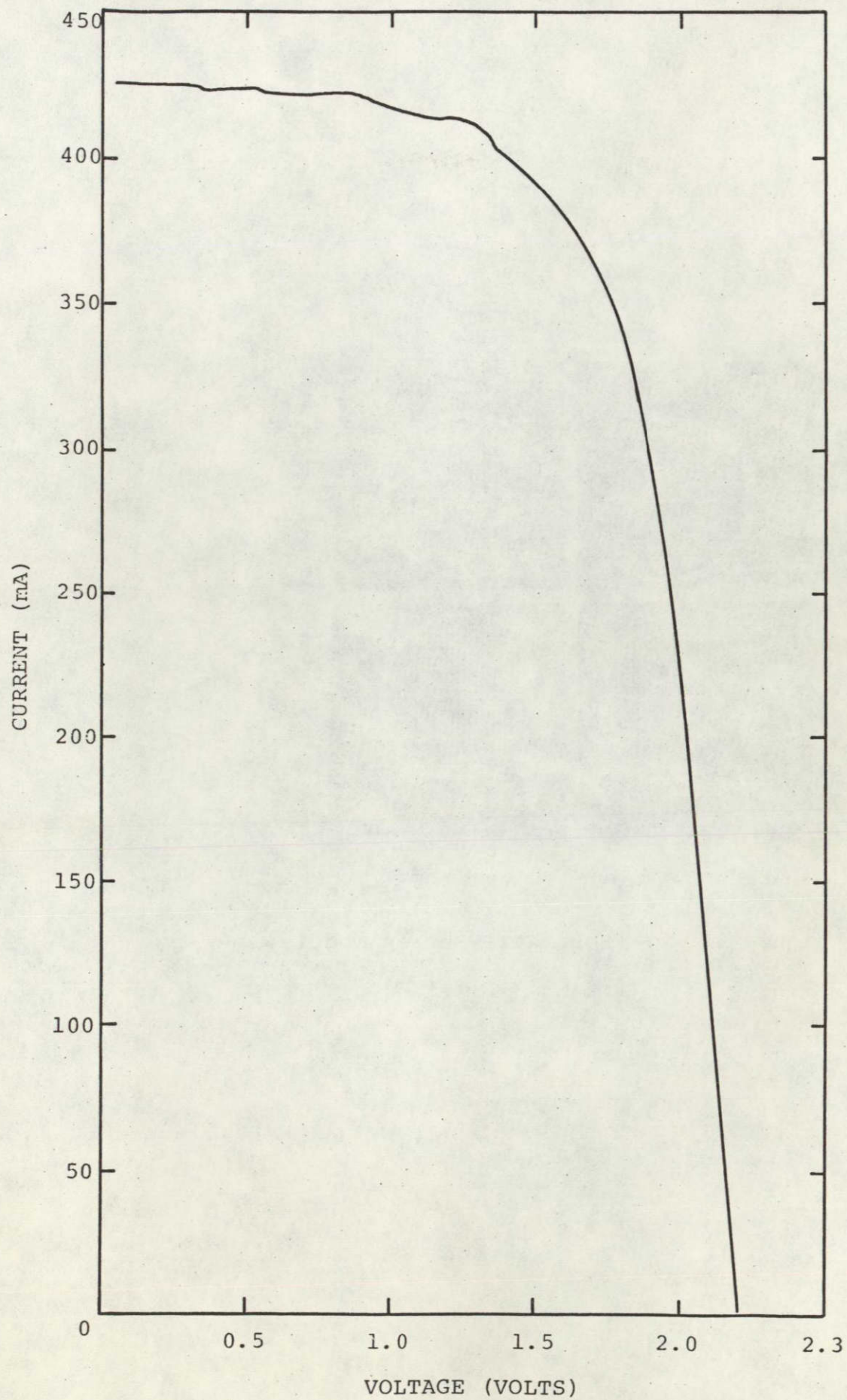


Figure 11. I-V Curve of Four Cell Series Module

of the glass to the bonding electrodes. Earlier experiments⁽³⁾ made with mold release compounds showed that it was possible to make bonds at temperatures in excess of 600°C without sticking problems. Complete evaluation of these materials in the interim bonder was impossible because of coating instability in the oxidizing environment of the early bonder.

Recently these experiments have been repeated in the controlled environment bonder. Coatings of Renite[®] R-Seal, sprayed onto mill finish stainless steel plates and baked at 200°C for 30 minutes, were used as electrode surfaces during deformation bonding of silicon to 7070 glass. Good deformation bonds were produced. The glass surface did become clouded by material transferred from the electrode. While most of this contamination was easily removed chemically, the presence of any surface impurity is undesirable. Experiments will continue. The electrode surface degraded with successive uses but remained usable for at least six runs. Coating of Renite[®] S24 were also tried, again without sticking. Glass surface contamination was less than with R-Seal, but electrode life was limited to a single run.

Polished vitreous carbon has also been identified as a promising candidate for an electrode material⁽³⁾. Initial cost, polishing requirements and brittleness are serious

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drawbacks of this material. These may be offset if long term use without maintenance is possible. Extreme deformation bonding experiments with this electrode will be tried.

The electrode problem encountered in production of the Type III modules is one of the most difficult of this program. Thus this demonstration of complete deformation bonding represents a significant step toward the realization of a fully integral glass encapsulated solar cell module.

3.0 CONCLUSIONS

During the third quarterly period of this program the following progress can be reported.

- (1) The controlled environment bonder has become fully operational.
- (2) Bonds have been made on a variety of non oxidizing atmospheres and have been found to be far superior to those made in ambient air.
- (3) Working solar cells have been electrostatically bonded to 7070 glass without serious deterioration of their electrical properties.
- (4) Bonds between glass and a variety of metals, including molybdenum, tantalum, titanium, chromium and silver have been demonstrated for the first time.

- (5) Solar cells, without contacts, have been bonded to 7070 glass, coated with silk screened silver metallization, to produce working one cell modules.
- (6) Bonds between solar cells and the rough surface of as-pressed 7070 glass has been made.
- (7) Repressing of as-pressed 7070 has been demonstrated.
- (8) Initial shear strength and hermeticity test samples have been delivered to JPL. Tests have demonstrated the excellent strength of electrostatic bonds.
- (9) Electrically functioning four and five cell modules have been produced both in series and parallel configurations.
- (10) Many of the design features of the three deliverable module types have been identified.
- (11) Large scale deformation bonding has been accomplished.

4.0 APPENDICES

4.1 New Technology

No new technology has been identified during the period of this report.

4.2 Program Plan

During the next three month period, efforts will concentrate on development and production of the three module types. Delivery of the Type I modules will be made early in this period while Type II should be completed towards the end of the quarter. Development of the fully integral Type III module will proceed in parallel with this production.

Production of additional shear strength and hermeticity samples will be accomplished as bonding time permits. Bonding of a variety of JPL supplied silk screened coatings will also be done.

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